Miniaturized Camera Systems for Microfactories

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Abstract. This paper presents our work on finding an alternative for standard machine vision equipment to be used in microfactories where small working spaces raise the need for miniaturized equipment. We tested three commercially available miniaturized camera modules used, for example, in mobile phones and compared them against two standard machine vision cameras. In the tests, we compared four selected factors: camera dynamic capability, image distortions, edge sharpness, and smoothness of image brightness.

Keywords: Microfactory, desktop factory, machine vision, miniaturized camera systems

1 Introduction

Desktop and microfactory equipment refers to manufacturing and assembly equipment that can be placed on desktop and moved easily by human power. For example, the microfactory concept developed at Tampere University of Technology (TUT) [1] uses stand-alone factory modules that have dimensions of 300 x 220 x 200 mm and that have a working envelope of 180 x 180 x 180 mm. Because of the very small working envelope, all used equipment needs to be highly miniaturized. Fig. 1 shows the TUT microfactory module where the left part of the module is reserved for control electronics and the larger part on the right is the work envelope.

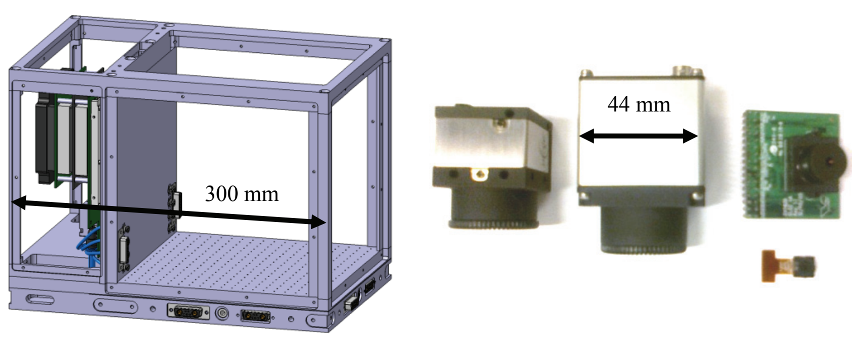


Fig. 1. TUT microfactory module (left) and tested C-mount cameras (without lenses), 2 megapixel, and 5 megapixel camera modules (right). Green circuit board under 5 megapixel module is an adapter board for evaluation purposes.

Typical assembly and manufacturing operations implemented in desktop and microfactories need or at least benefit greatly from the use of machine vision. Cameras can, for example, locate parts to be assembled, make dimensional measurements, or perform other quality assurance tasks. However, integrating standard machine vision cameras with standard C-mount or even S-mount optics to the small working envelope of a microfactory is extremely difficult because of their relatively large size. Therefore smaller cameras with smaller optics are needed. In this paper we present our work on finding an alternative for normal machine vision equipment.

2 Tested Cameras and Camera Modules

We tested three miniaturized camera modules used, for example, in mobile phones and compared them against two normal machine vision cameras with C-mount optics. Table 1 and Fig. 1 show tested cameras. In the tests, we used a C-mount lens with nominal focal length of 12 mm (type JHF12MK) from SpaceCom [2]. The length of the C-mount lens (about 36 mm for the lens used) is not included in the physical size mentioned in Table 1 but it has to added to depth length of C-mount cameras. For camera modules, the physical depth dimension includes the integrated lens.

Table 1. Tested C-mount cameras and camera modules.

Camera	Type	Resolution	Pixel Size	Full Well Capacity	Physical Size (mm)	Manufacturer
UI-1540-M (C-mount)	Grayscale (CMOS, USB)	1280 x 1024 (SXGA, 1.3 MP)	5.2 µm	40 000 e-	32 x 34 x 38 (W x H x D)	Imaging Development Systems [3]
UI-6240-SE-M (C-mount)	Grayscale (CCD, GigE)	1280 x 1024	4.65 µm	12 000 e-	44 x 34 x 60 (W x H x D)	Imaging Development Systems [3]
Omni-Vision OV-07640	RGB color, CMOS	640 x 480 (VGA, 0.3 MP)	4.2 µm	35 000 e-	6 x 6 x 5 (W x H x D)	OmniVision Technologies [4]
Omni-Vision OV-2640	RGB color, CMOS	1600 x 1200 (2 MP)	2.2 µm	12 000 e-	8.5 x 8.5 x 5.5 (W x H x D)	OmniVision Technologies [4]
Omni-Vision OV-5620	RGB color, CMOS	2592 x 1944 (5 MP)	2.2 µm	Not known	21 x 19 x 16 (W x H x D)	OmniVision Technologies [4]

Tested miniaturized camera modules use integrated lenses and custom made, highly integrated, electronics making their physical size very small. In addition, due to large manufacturing volumes they are cheap making them an interesting alternative for normal machine vision equipment. As such, tested miniaturized camera modules do not have connectors or software capability to be connected directly to PC as normal machine vision cameras. For testing and evaluation, manufacturer offers an evaluation kit with USB and/or Ethernet connectors and software enabling connection to PC.

3 Test Targets and Image Capturing

We tested each camera to find out 1) how much geometrical distortions images have, 2) how uniform image brightness is, 3) how sharp edges images have, and 4) how well cameras can detect dark and bright objects at the same time (dynamic capability). For this purpose, we used targets shown in Fig. 2. Test targets were: a) a checker board pattern for calibrating and calculating image geometrical distortions, b) uniform mid gray (pixel value 128, max 255) for checking brightness uniformity, c) two patterns with black and white bars and slanted squares for evaluating edge sharpness, and d) a pattern with 17 regularly distributed grayscales ranging from completely black (pixel value 0) to completely white (pixel value 255) for evaluating the dynamic capability of the imaging system. Final test target having some common objects is only used for visual estimations.

Fig. 2. Test targets imaged with OmniVision VGA camera module. Red rectangles on top of slanted square target indicate areas where edge sharpness was evaluated.

The targets were printed on normal A3 and A4 size papers with high quality color laser printer using 1200 dpi printing resolution. We took three images of each target in a room with no windows and normal office illumination created with fluorescent tubes in the ceiling. When taking images, we adjusted the distance between camera and target so that the field-of-view (FOV) was always slightly over 300 mm wide fitting A4 size paper. We also took care that the targets were always in the same orientation. With C-mount cameras we used the same lens with same aperture size. Before and after taking images, we measured illumination intensity in FOV corners and center with an exposure meter commonly used in photography. To avoid effects created by image compression, we saved all images in bitmap format. Table 2 summarizes imaging conditions.

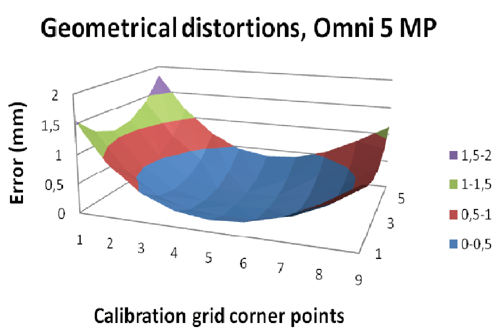
Table 2. Imaging conditions when taking test images.

	UI-1540	UI-6240	Omni VGA	Omni 2 MP	Omni 5 MP
Lens-target distance (mm)	584	656	393	371	487
Camera integration time (ms)	119	57	Not known (auto-exposure)	Not known (auto-exposure)	Not known (auto-exposure)
Illumination intensity (exposure values)	7.5 – 7.7	7.5 – 7.7	7.4 – 7.6	7.4 – 7.6	7.4 – 7.6

4 Analysis and Test Results

4.1 Image Geometrical Distortions

For calculating image distortions, we used calibration toolbox for Matlab [5] to detect the corners of the checker board pattern to get a 9 x 6 matrix of image coordinates. After that, we used calibration method developed by Heikkilä [6] and implemented in Matlab [7] to calibrate the camera + lens system and to calculate the corrected corner image coordinates. Finally, we calculated the distance in pixels between the original, measured, and the corrected image coordinates. Knowing the camera resolution and FOV size in millimeters, we calculated the spatial resolution (mm per pixel) and used that to transform pixel distances to millimeters. Fig. 3 shows these errors in graphical format for OmniVision 5 MP camera module. The shape of the error pattern was similar for all cameras and camera modules: largest errors are in corners. Table in Fig. 3 shows the average and maximum distortions in millimeters.



	Avg (mm)	Max (mm)
UI-1540	0.47	1.42
UI-6240	0.32	1.19
OV VGA	0.32	1.37
OV 2 MP	0.74	1.51
OV 5 MP	0.51	1.82

Fig. 3. Geometrical distortions in 9 x 6 calibration points for OmniVision 5 MP camera module and average and maximum distortions for all tested cameras and camera modules.

4.2 Image Brightness Uniformity

To evaluate the uniformity of image brightness, we divided images to 10 x 8 equally sized windows and calculated the average pixel intensities for each window. In these calculations, we did not consider the small variations in illumination intensities in different parts of camera FOV, because they were constant and small. We scanned the target with a normal desktop scanner using 600 dpi resolution and made the same analysis for the scanned image to verify target brightness. Even though the test target was printed with high quality laser printer to constant mid gray color (pixel value 128, max 255), it proved to have small variations in measured gray values (brightnesses). As leftmost graph in Fig. 4 shows, scanned target brightness changed relatively randomly whereas OmniVision 2 MP images were substantially brighter in center part of the image.

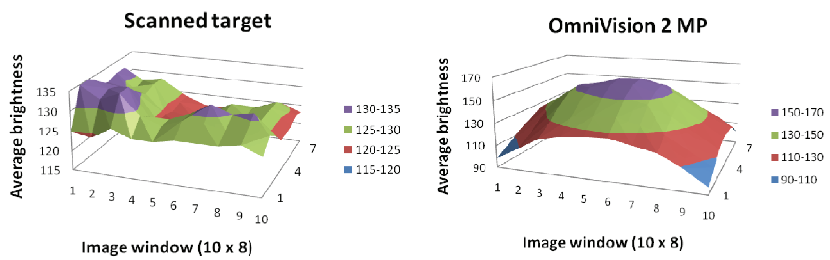


Fig. 4. Measured average pixel brightnesses for 10 x 8 image windows of scanned target (left) and for OmniVision 2 MP image (right). Graphs have different scales in Z direction.

Table 3 lists minimum, average, and maximum brightness values for scanned target and for all cameras and camera modules. Images captured with C-mount cameras had relatively even brightness whereas all camera modules produced images where the center part of the image was noticeably brighter than corners and edges.

Table 3. Image brightness uniformity test results for all cameras and camera modules.

	Scanned	UI-1540	UI-6240	OV VGA	OV 2 MP	OV 5 MP
Min	121.0	96.0	96.0	71.0	96.0	74.3
Average	127.0	104.3	101.2	98.8	132.8	110.3
Max	135.0	113.0	115.0	118.7	161.0	134.7
Standard deviation	3.4	4.2	4.9	12.1	15.9	16.9
Max - Min	14.0	17.0	19.0	47.7	65	60.3

4.3 Edge Sharpness

We used ImaTest software [8] to calculate two measures for edge sharpness from 10 different positions from the slanted squares test target (see Fig. 2). First measure is Modulation Transfer Function (MTF) and especially MTF50 value. MTF50 value refers to frequency when contrast between input and output has dropped to 50% of its original value. In practice this means, for example, distance between black and white bars where contrast between black and white has dropped to 50% of original making bars seem blurry. ImaTest's SFR function calculates MTF50 value in line widths and divides it by picture height to compensate different picture resolutions. Second measure for edge sharpness is the distance, measured in pixels, from background to target pixel brightness values giving the "steepness" of the edge. ImaTest calculates 10% - 90% rise distance and scales it to picture height as in MTF50 calculations.

Fig. 5 shows MTF50 value in line widths (LW) divided by picture height and 10% - 90% edge rise distance also scaled with picture height (PH). In both graphs, the higher the value the better it is. Horizontal axis in both graphs refers to the 10 different edges where, for example, LTV means Left Top corner Vertical edge and MiH means Middle square and Horizontal edge (see Fig. 2).

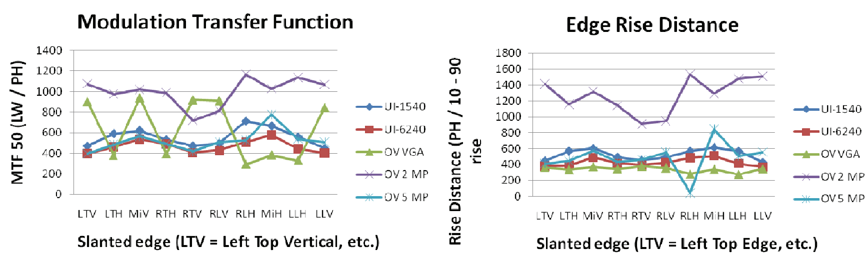


Fig. 5. Edge sharpness results.

Tested camera modules use Bayer mosaic filter to detect colors. This commonly used technique is simple but, as a drawback, it adds (colored) artifacts around target edges. Tsai and Song [9] explain this in detail and propose a method to reduce color artifacts. Tested camera modules clearly do not use such methods as all images captured with all camera modules show these artifacts as colors next to target edges on black and white targets. Fig. 6 shows a close-up on bar pattern imaged with OV 2 MP module. Graph on right in Fig. 6 shows red, green, and blue pixel intensities measured in horizontal direction. This graph shows that red, green, and blue pixel values have peaks in slightly different positions making some pixel columns seem colored.

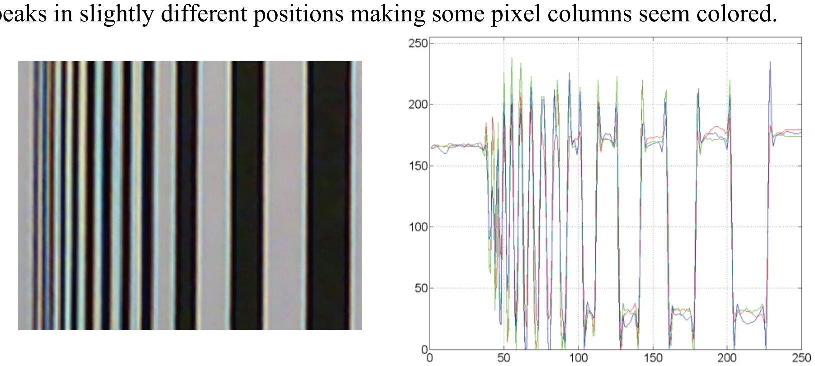


Fig. 6. Close-up on edge pattern showing colored artifacts.

4.4 Dynamic Capability

We evaluated camera dynamic capability by using a pattern with 17 different grayscales ranging from completely white (pixel value 255) to completely black (pixel value 0) with even steps. ImaTest's Stepchart feature calculated average pixel values for each 17 steps for all cameras, camera modules, and also for scanned target. Fig. 7 shows these results. When taking images with C-mount cameras, we adjusted camera integration time so that the white step would be almost overexposed (pixel value almost 255). Camera modules used automatic exposure and therefore white steps do not appear completely white but have pixel values around 180.

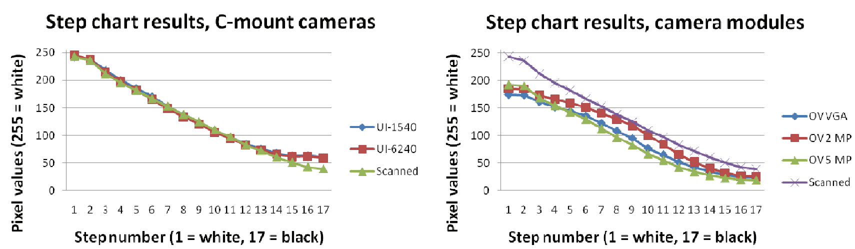


Fig. 7. Measured image brightnesses of 17 gray steps for C-mount cameras (on left) and for camera modules (on right).

5 Discussion and Conclusions

Based on these tests, tested miniaturized camera modules provide good enough quality images to be, in most applications, realistically comparable with standard machine vision equipment. Even though tested camera modules have higher pixel resolutions than C-mount cameras, one has to remember that using Bayer mosaic filter reduces "true image resolution" because pixel (color) values are interpolated from several neighboring pixels. Another drawback resulting from Bayer filter are the (colored) artifacts on target edges possibly making edge detection more difficult than when using monochrome (grayscale) cameras. Edge sharpness and image geometrical distortions were similar in all tested cameras and camera modules. Variations in image brightness are probably the most significant difference between tested cameras and camera modules.

One fundamental difference between standard machine vision cameras and miniaturized camera modules is the level of automatization: Camera modules have several automatic software features manipulating raw camera image before outputting it; for example auto exposure setting, automatic white balance, and edge enhancement are just a few features camera modules automatically adjust. Such features are convenient when the goal is to (automatically) make images look good to human eye. In typical machine vision applications, however, we want to control, or at least know, what parameters were used when image was captured in order to able to reliably compare images from the same scene. Tested camera modules have limited and/or poorly documented methods to control image capturing parameters and, considering their use in machine vision applications, this is a definite weakness for them. Other weaknesses are their short lifespan and limited availability and support at least for small customers.

On the other hand, considering desktop and microfactory applications, the extremely small size of miniaturized camera modules is a distinctive advantage. Small size enables easy integration and placing cameras to places where normal machine vision cameras are impossible to fit. Further advantage of camera modules is their low price: the modules tested here cost approximately 20 € per piece. Therefore it would be economically feasible to use multiple cameras in each microfactory module enabling completely new ways of monitoring and measuring production.

5.1 Future Work

As mentioned earlier, tested camera modules do not have necessary connectors or software to be connected directly to PC. Therefore we have started to design a circuit board to which we can connect four OmniVision 2 MP modules and transfer image data to PC over Ethernet connection. Our plan is to fit one or more four camera units in our microfactory module. This gives us, for example, a view of the working area from several directions enabling measurements in three dimensions using stereo vision and/or photogrammetry. Second application could be to use different exposure settings in cameras looking at the same area enabling imaging with better dynamics, i.e. detecting very bright and dark objects at the same time. Third possibility is to combine several partially overlapping images into one high resolution image. Researchers at Stanford have implemented these using up to 128 conventionally sized cameras [10]. Our aim is to achieve similar results in microfactory environment using miniaturized camera modules.

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